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Reviews of power systems and environmental energy conversion for unmanned underwater vehicles

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ABSTRACT

The power supply for unmanned underwater vehicles has been an important research point since the vehicles were invented. The power systems and environmental energy conversions for the vehicles are reviewed in the paper. Several topics are represented: problems and general solutions for unmanned underwater vehicles power supplies; the mechanisms and structures of tether power system; characteristics of several batteries; the characterization of potential environmental energy, and energy conversion for unmanned underwater vehicles. Docking stations for underwater vehicles continuation are also represented in the paper. Some typical vehicles powered by the power systems and their performances are listed and analyzed.

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Contents

1. Introduction

Oceans are abundant in kinds of marine resources, such as halobios, mineral and ocean energy. Most of these resources are not fully developed to date. Therefore, techniques for ocean explorations are being researched, and many new devices and equipments are developed. Unmanned underwater vehicles (UUVs) are the most widely used equipments in modern times. They are unoccupied, reliable and highly maneuverable. The unmanned undersea vehicles (UUV) program was created with the goal of extending knowledge and control of the undersea battlespace through the employment of clandestine off-board sensors [1]. They are applied for difficult working conditions instead of

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person itself. An underwater vehicle will complete missions as instructed, and exchange information and data with the ship or station. Generally speaking, UUVs can be applied for scientific research, acquiring information of oceans and life-forms. They can also be used for inspections and operations of the facilities under the water. The present unmanned underwater vehicles can mainly be classified as three types, remote operated underwater vehicles (ROVs), autonomous underwater vehicles (AUVs) and autonomous underwater gliders (AUGs) [2–4]. They are applied to complete different missions under different working conditions [5,6].

UUVs are quite well developed and widely applied in practice. However, there are still some techniques needed improving, such as control, communication, navigation and power supply [7–11]. Among these techniques, power supply is especially important and crucial. Power supply does affect UUVs' working duration and mission completion. These years, institutions and scientists have dedicated great efforts to the research of power systems and new energy sources. A great progress has been made, and the techniques that address such an issue include [11,12]:

1) *Tether method*. Tether connects a ROV to the LASH ship, and provides continuous electrical power over wires or cables inside.
2) *Battery method*. It is especially applied for AUVs and AUGs. Primary batteries, secondary batteries, fuel cells and semi-fuels are commonly used.
3) *Environmental energy conversion*. Environmental energies are used as energy sources to power underwater vehicles, such as solar energy, ocean thermal energy and wave energy.
4) *Docking station establishment*. Docking station establishment is able to increase the continuation of an underwater vehicle. It is a complement to battery method.

Besides, there are several other methods in consideration, such as nuclear sources application [13]. They are feasible in theory, but unsatisfactory in practice. There are environmental and legal concerns which make them inaccessible to most groups. In the following paper, we will represent the researches of power supply for unmanned underwater vehicles.

2. Tether power systems

According to Kevin Dowling in [12], a tether power system is often mentioned as an alternative to provide power for a mobile system. A tether connects a mobile system to an off board power source, providing continuous power over a wire or cable inside. It can also provide communications to the mobile system. Tethers are used early and widely, because they are operated simply and safely. Generally speaking, a tether power system owns a reel system (or a winch system) and tethers. A reel system is fixed in a station, and a winch system is installed in the mobile system. Tethers can be fed and extended by using either system.

ROVs are developed to complete kinds of missions instead of persons. Therefore, tether power systems are used to provide electrical power and communications, as shown in Fig. 1.

Tether power system in a ROV generally consists of a reel system, a tether management system (TMS) and tethers. A reel system is fixed in a LASH ship, and it deploys tethers to a ROV, adjusting tether length and the working range. Tethers are always lightweight, and prone to moving when waves interrupt. The interruptions are no good to the ROVs' working, and a TMS [14] is needed. It is positioned between the LASH ship and the ROV under the water. TMS provides additional weight, and cancel the interruptions, especially important for an engineering ROV. Besides, it can work as a relaying part for ROVs. It is notable that TMS is not quite necessary for an observation ROV, because it will affect the vehicle's flexibility. Tethers are used to connect LASH ships,

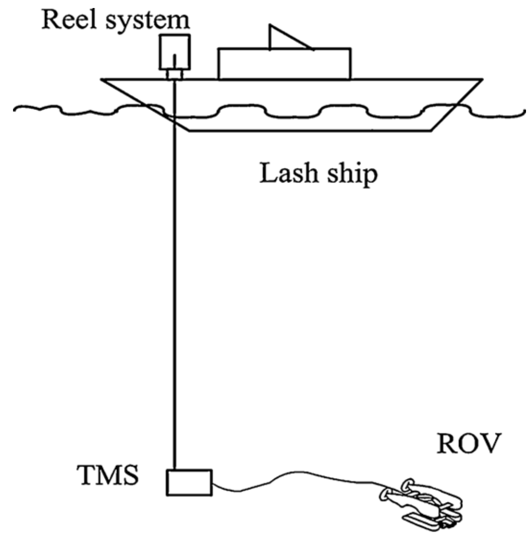

Fig. 1. ROV with tethers.

TMSs and ROVs, respectively. Typically, tethers are a mix of power and communication lines with advanced tethers, integrating fiber optics or coaxial cables. A tether is wrapped by high-pressure layers. Stainless steel wires or oil-filled tubing can be used to protect cables from corrosion in seawater. The tether between TMS and ROV contains foaming material outside; it has the same density as marine water, to provide neutral buoyancy [15].

According to the research, hundreds of ROVs are equipped with tether power systems, including the heavy-work class, light-work class, mini class and pipe liner [16]. Jason/Medea is an engineering ROV system [17]. It has two parts, Jason and Medea. Jason is a ROV designed and built by Deep Submergence Laboratory of Woods Hole Oceanographic Institution (WHOI) in USA. It is used for seafloor operation without leaving the deck of a ship. Medea is heavy, about 1200 pounds, it serves as a shock absorber, buffering Jason from the movements of the ship, while providing lighting and a bird's eye view of the ROV during seafloor operations. In Jason/Medea, there is a 10-kilometer fiber-optic tether to deliver electrical power, lasting for 21 h one time averagely (Fig. 2).

3. Batteries

Batteries have been used as common power sources for many households and industrial applications and scientific researches. They are small with relatively high energy density, and provide electrical energy when discharging. According to the chemical reaction and operating life cycles, batteries can be classified into two general categories [18]:

1) *Primary batteries*. The chemical reactions inside the batteries are irreversible. And the primary batteries are designed to be used once and discarded, and cannot be recharged.
2) *Secondary batteries*. The chemical reactions inside the batteries are reversible. So the secondary batteries can be recharged and used for multiple times.

There are also some other battery types, like fuel cells and semi-fuel cells. A fuel cell is an electrochemical cell that converts energy from oxygen and fuel into electrical energy [19]. They are characterized by higher efficiency, less pollution and no outgassing. Semi-fuel cells are another kind of fuel cells. They utilize metal alloys, air cathodes and an electrolyte for reaction, and provide much higher energy densities [12].

Table 1
Underwater vehicles powered by primary batteries and performances.

Name	Size	Battery	Endurance/Range	Depth
Slocum battery	1.5 m	Alkaline cells	500 km, 20 days@0.6 kts	200 m
Spray glider	2.15 m	Primary lithium sulfuryl chloride	7000 km, 770 days@0.6 kts	1500 m
Seaglider	3.3 m	Primary lithium thionyl chloride	4600 km, 200 days@0.6 kts	1000 m
Autosub-1	7 m	Alkaline cells	50 h/263 km	300 m
Seahorse	28 ′5	Alkaline cells	500 nm	1000–2000′

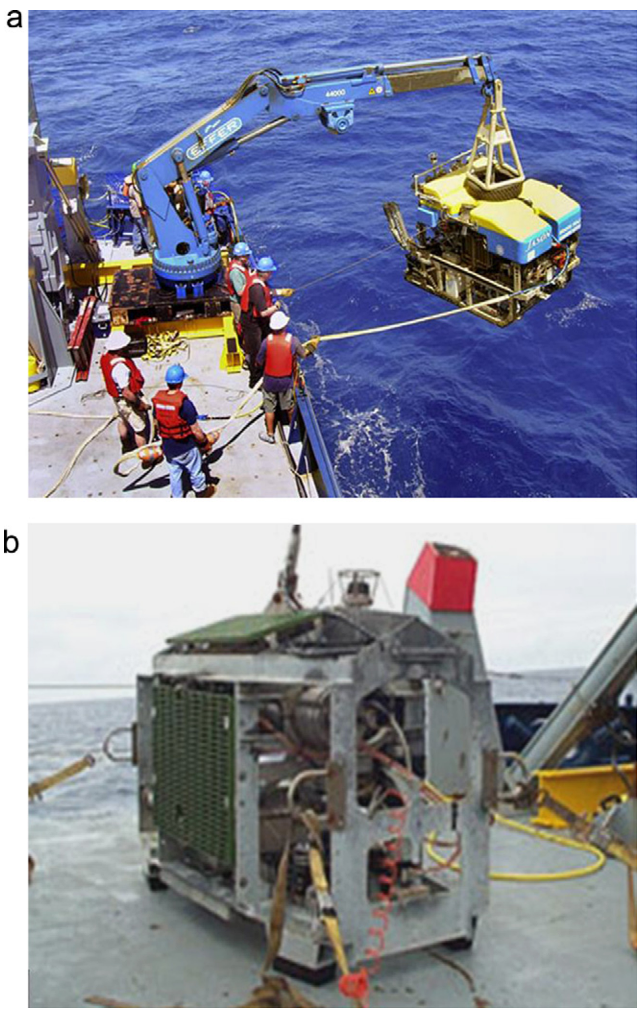

Fig. 2. (a) Jason and (b) Medea.

Power supply by using batteries is a good way for those underwater vehicles without tethers, such as AUVs and AUGs. Comparing with the tether power system in ROVs, batteries possess some advantages, such as silent operation, ease of speed control and simplicity of use. These batteries mentioned above can also be applied for UUVs. Primary batteries and secondary batteries are initially used in AUGs and some AUVs, such as alkaline cells, lithium primary cells, ni-cad cells and silver-zinc cells [20]. Fuel cells and semi-fuel cells are newly developed and applied in UUVs, and they are used in some AUVs, such as PEFC, PEMFC and aluminum oxygen cells [21–23]. Besides, batteries are used in a hybrid way to increase the working duration [12,24].

3.1. Primary batteries

Primary batteries are not rechargeable and are still used for a variety of several applications (such as underwater vehicles power supply) although secondary batteries are preferred for reasons of cost and ease of use. Common primary batteries for underwater vehicles are mainly alkaline cells and lithium primary cells [20]. Alkaline cells are the simplest batteries to use. They have quite a high energy density, approaching 140 Wh/kg. They are safe, inexpensive and easy to use. However, they do tend to outgas hydrogen when stored for a long time. Lithium primary cells are the best choice when demanding high energy density, almost 375 Wh/kg. The cells have some advantages over alkaline cells, such as low weight, flat discharge characteristics, long shelf life and a long operating life. But the cells are quite costly. These two primary batteries are widely used initially in AUGs and AUVs. Table 1 has listed some typical primary batteries powered vehicles and performances [25–29].

3.2. Secondary batteries

Secondary batteries are growing more and more popular in supplying power for UUVs. Compared with primary batteries, secondary batteries can be recharged and used for many times with a longer operating life. There are many kinds of secondary batteries, and the batteries for UUVs mainly include lead-acid cells, silver-zinc cells, ni-cad cells, and lithium ion cells, etc. [20]. Lead-acid cells are the oldest form of secondary batteries. They are simply operated and widely used, but large and heavy. Silver-zinc cells are in high energy density, but costly and short with lifetimes, about 100–250 cycles. Ni-cad batteries are widely used when needing high current. They are inexpensive and quite available, but heavier than the others. Lithium ion cells are small in size, and offer higher energy than other cells. But they are expensive and need charging carefully to avoid fire and burning. Table 2 has given the vehicles powered by secondary batteries and their performances [30–37].

Table 2
Underwater vehicles powered by secondary batteries and performances.

Name	Size	Battery	Endurance or range	Depth
MUST	25′–35′	Lead acid	Up to 24 h	2000′
OEX	7′	Ni-cad	12 h	1000′
CR-02	4.5 m	Silver zinc	25 h	6000 m
Remus family	1.6–3.84 m	Lithium ion	10–70 h	100–6000 m
HUGIN 1000	4.7 m	Li polymer pressure tolerant	24 h@4 kts	1000–3000 m
Bluefin-12	84″-150″	Li polymer pressure tolerant	10–23 h	200 m
Odyssey IIx	2.2 m	Li-polymer	8 h/44 km	3000 m
Fau Morpheus	1.5–3 m	Ni-MH	Unavailable	Unavailable

Table 3
Several types of fuel cells and their working features.

Type	Operating temperature	Fuel	Exhaust heat utilization	Features
PAFC	150–200 °C	Natural gas, LPG, etc.	Hot water, steam	Low temperature operation
MCFC	600–650 °C	Natural gas, coal gasification gas, etc.	Gas turbine, steam turbine	Extensive use of fuel/internally reformable
SOFC	800–1000 °C	Natural gas, coal gasification gas, etc.	Gas turbine, steam turbine	Extensive use of fuel/internally reformable
PEFC	Up to 80 °C	Natural gas, hydrogen, methanol, etc.	Hot water	High energy density, low temperature operation
PEMFC	60–80 °C	Hydrogen	Hot water	High energy density, low temperature operation

3.3. Fuel cells

Fuel cell was firstly designed by Welsh scientist and barrister Sir William Robert Grove in 1839 [38]. It can provide quite high electrical energy by reaction of fuel and oxygen without combustion. The cells have many advantages over primary batteries and secondary batteries, such as higher efficiency, less pollution and no outgassing. Therefore, the fuel cells are ideal to power underwater vehicles.

Depending on type of the electrolytes, there are several fuel cells, phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), polymer electrolyte fuel cell (PEFC) and proton exchanger membrane fuel cell (PEMFC). They are different in operating temperature, fuels, exhaust heat utilization and some other features [39], as is exhibited in Table 3.

Not all fuel cells above are suited to underwater vehicle applications. Seen from Table 3, PEFC and PEMFC are much better choices for powering UUVs by comparison. Firstly, the fuels are accessible, such as hydrogen and natural gas. Secondly, fuel cells are easy to start and stop. The highest operating temperature of PEFC is 80 °C, and PEMFC is among 60–80 °C [22]. Thirdly, exhaust heat utilization is simple and safe, just hot water. Therefore, PEFC and PEMFC are started to be applied for some AUVs.

Japan Agency for Marine-Earth Science and Technology (JAMSTEC) started to develop the world's first AUV Urashima, powered by PEFC In 1998, and lithium ion cells as an auxiliary power source [40]. Later, it developed another PEFC-powered AUV, AUV-EX1 [41]. In 2004, a hydrogen-fueled AUV "DeepC" debuted in German. The project was funded by the German Federal Ministry for Education and Research (GFMER) [42]. Tianjin University in China has also developed an underwater glider Dragon. It is powered by PEMFC [22].

The power system for Urashima was developed by Mitsubishi Heavy Industries Ltd. (MHI). It is a totally closed cycle fuel cell system, as is shown in Fig. 3. The fuel cell system is positioned in a pressure vessel, consisting of fuel cell stacks, reaction water tank, humidifier and heat exchanger. Oxygen tank and fuel tank are also needed. Oxygen is containing in an independent tank. Fuel tank is positioned in another pressure vessel, containing metal hydride as fuel. Oxygen and hydrogen generated are imported into the fuel cell system. Therefore, electricity is generated through the reaction. In the fuel cell system, the temperature and humidity are controlled all the time.

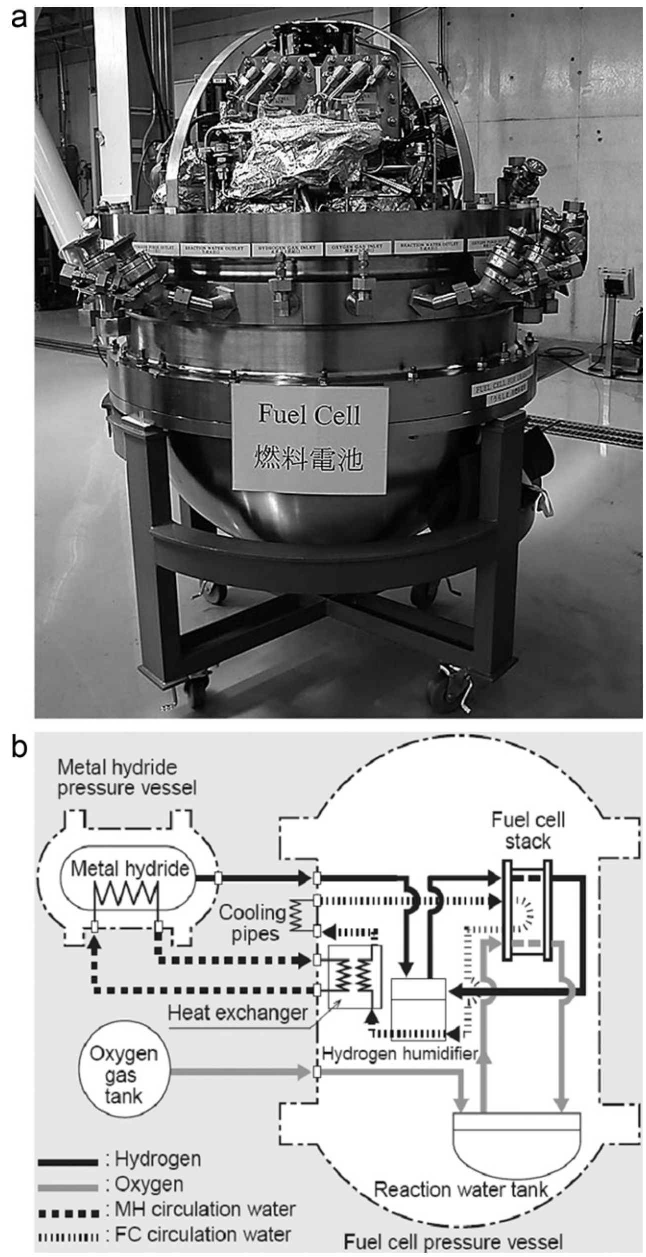

Fig. 3. (a and b) The fuel cell system in Urashima.

3.4. Semi fuel cells

Semi fuel cell is a kind of metal air cell, using the oxidation of a metal with oxygen to produce electricity [12]. In semi fuel cells, metal anodes and air cathodes are utilized, alkaline or saline is used as an electrolyte. The cells can provide energy densities of up to 500 Wh/kg, much higher than common batteries. There are several semi fuel cells researched, such as aluminum air cells, zinc air cells and lithium air cells. The semi fuel cells can also supply power for underwater vehicles, and the underwater versions can utilize seawater as the electrolyte (Fig. 4).

The US Navy XP-21 AUV was the first AUV worldwide to complete sea trials of an Aluminum Energy system in 1993 [43]. The energy system was invented by Fuel Cell Technologies Ltd. (FCT). Since then, FCT developed kinds of high endurance Aluminum Energy (AE) semi-fuel cell systems for various underwater applications [44]. The AE system and an updated one were developed for sea trials of Canadian Navy Autonomous Remote Controlled Submersible (ARCS) AUV in 1994 and 1997 [45]. And a Very-High

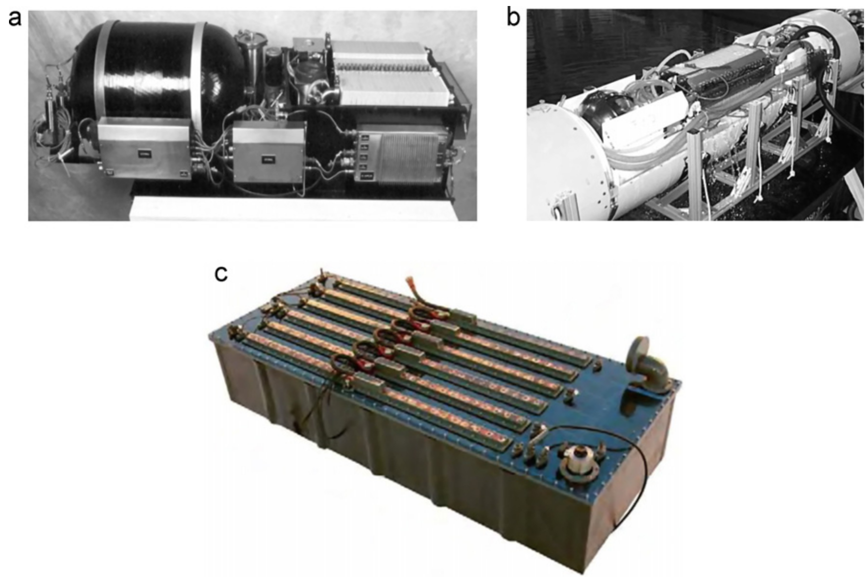

Fig. 4. Semi fuel cells for UUVs: (a) AE system for ARCS, (b) energy system for ALTEX, and (c) ALHP FC for HUIGIN AUVs.

Endurance Energy System was developed for the Atlantic Layer Tracking Experiment (ALTEX) AUV, which was part of the National Ocean Partnership Program [46]. HUGIN 3000 and HUGIN 4500 are powered by Al/HP semi fuel cells of 45 kWh and 60 kWh, respectively [47]. The semi fuel cells installed in HUGIN AUVs are ALHP FC, developed by the Norwegian Defense Research Establishment (FFI) and the Kongsberg Maritime. The fuel cells are especially available for the HUGIN AUVs.

3.5. Hybrid power system of batteries

Power provided by batteries is limited. The batteries can deliver small amounts of energy for long periods of time, but cannot deliver high power for short durations. Therefore, hybrid power systems are applied [12]. They can provide small amount of energy continuously and high power for short durations, to satisfy different working conditions. Hybrid power systems are also applied in some unmanned underwater vehicles. According to Griffiths in [48], hybrid fuel/cell battery energy systems for AUVs can be modeled realistically by using virtual test bed (VTB), a tool for modeling power systems. And Q. Cai proposed hybrid fuel cell/battery power system for underwater vehicles [24]. Urashima and AUV-EX1 concerned above are both mainly powered by fuel cells, and lithium ion cells are auxiliary power source. AUV-EX1 was developed to cruise for 300 km and 100 km powered by fuel cells and lithium ion cells, respectively [41] (Fig. 5).

Fig. 5. Urashima powered by a hybrid way.

4. Environmental energy conversion

So far, the UUVs' power supply by using tether power system and batteries are the main ways and research points in the world. However, the ways have their own drawbacks. ROVs are depending on the LASH ship via tethers, inconvenient for vehicles' expansion. AUVs and AUGs powered by batteries are so limited in duration, and they rely on the docking station if needing continuation. The vehicles' working range and continuation are greatly affected by the way of power supply. And the high cost is also needed to take into consideration. Therefore, it is necessary to improve and perfect these techniques. Besides, finding another way of power supply or new energy sources substituted is also available for UUVs.

Environmental energy is the most promising energy source. It exists almost everywhere, huge, green, clean and regenerative. There are kinds of environmental energy sources, such as solar energy, wind energy, ocean energy and geothermal energy [49]. Solar energy is the origin of almost all energy sources. The direct solar energy can be harnessed and converted into some useful energy sources, such as thermal energy by using heat engines and electrical energy by using solar panels [50]. Wind energy is abundant in storage. It can also be collected to generate electrical energy by using wind-driven generators. Large scale wind farms are established for electricity generation. According to World Wind Energy Report, worldwide nameplate capacity of wind-driven generators was 159.2 GW at the end of 2009 [51] (by June 2010 the capacity had risen to 175 GW [52]). The theoretical potential of ocean energy is quite giant, equivalent to 7110–15,110 GW [53]. It involves wave energy, tidal energy, saline gradient energy and ocean thermal energy. These energy sources are well developed and utilized in households and industries.

Environmental energy is also available for UUVs' power supply. Solar energy, ocean thermal energy and wave energy are the three most realistic energy sources for vehicles [54]. These energy sources can be captured and applied to driving some UUVs.

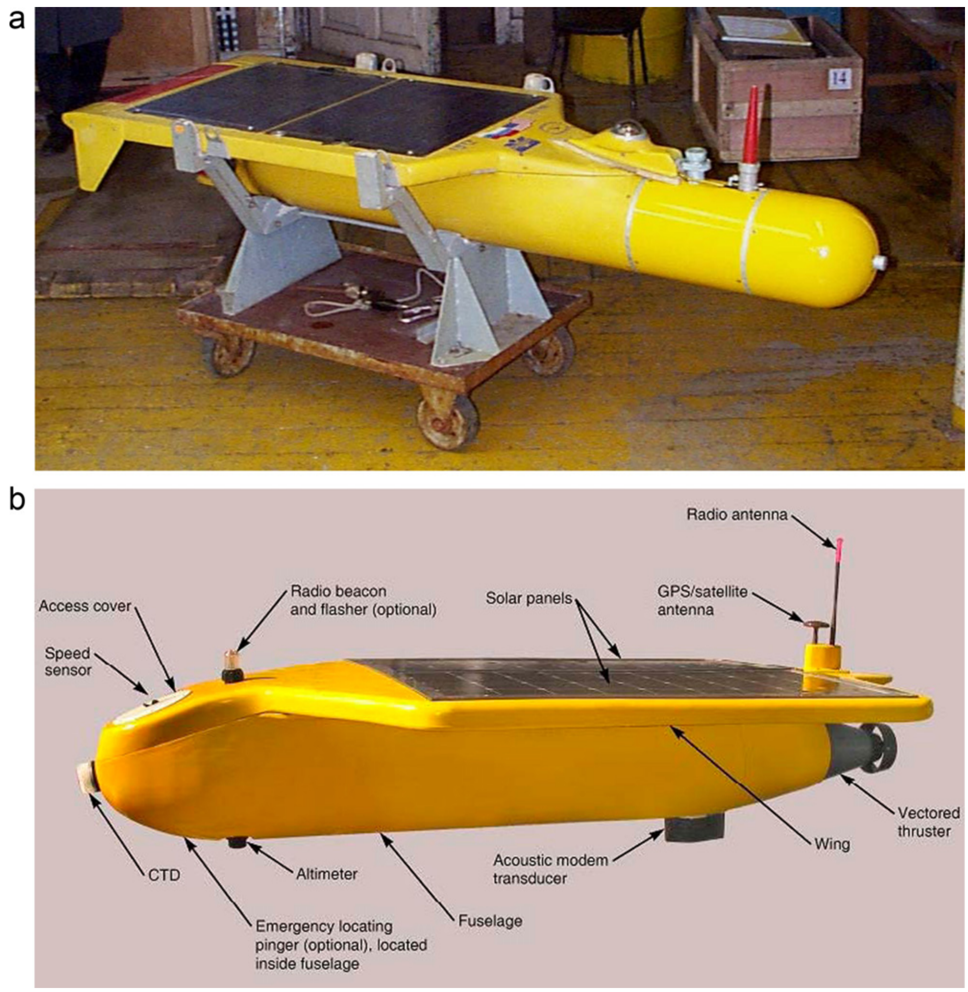

Fig. 6. AUSI series (a) SAUV-I and (b) SAUV-II.

4.1. Solar energy

As is mentioned above, solar energy can be converted into two energy forms, and the electrical energy is needed. The conversion of sunlight into electrical energy can be realized either by directly using solar panels or by indirectly using concentrated solar power systems (CSP systems) [55]. Solar panels (consisting of photovoltaic cells) are used commonly to generate electricity in commercial and residential applications. They are always installed together, because the conversion efficiencies available are only 10–12%, even though experimental models show 20–25% [56]. CSP system just uses mirrors or lenses to focus a large area of sunlight into a small beam.

The amount of solar energy available on the ocean surface varies significantly with latitude, seasons, and weather. The annual mean daily total horizontal solar radiation varies from less than 1 to about 12 kWh/m^2/day, according to Bahm in [57]. Therefore, it is a desirable way to generate electrical energy for UUVs via conversion from solar energy by using solar panels.

The SAUV series are the underwater vehicles powered by solar energy, as is shown in Fig. 6 [58]. The SAUV-I is designed and developed by AUSI, cooperating with the Institute for Marine Technology Problems (ITMP) and Russian Academy of Sciences (RAS). It was to validate various investigations undertaken during the Navy International Cooperation Program (NICOP). The power system consists of a Solarex MSX30L solar array, a microprocessor, a battery gas gauge and charge controller, and a ni-cad battery stack [56,59].

The SAUV-II is developed by AUSI, Falmouth Scientific Inc. (FSI) and Technology Systems Inc. (TSI). It was designed for long duration missions such as monitoring, surveillance and station keeping, with bi-directional communications to shore. The SAUV-II is equipped with 1.0 m^2 solar panel and a 32-V, 2-kWh energy system. The system is composed of 288 commercially available lithium ion cells. The SAUV II charging configuration is shown in Fig. 7.

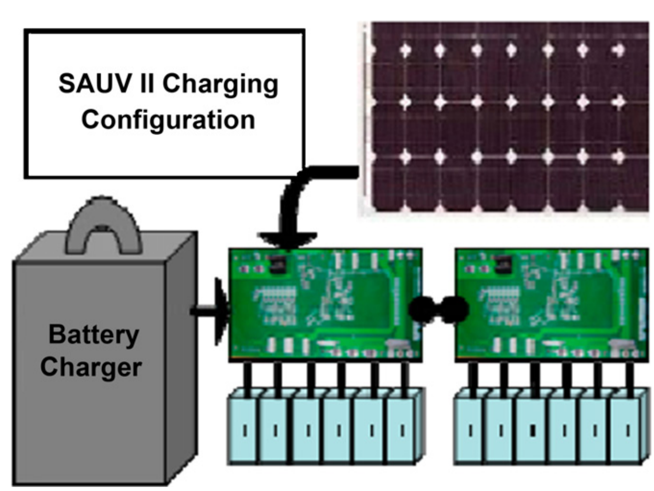

Fig. 7. The lithium-ion solar panel, energy manager, and batteries.

Fig. 8. Slocum Thermal Glider.

4.2. Ocean thermal energy

As we know, heat is accumulated in water due to sunshine. The temperature and heat vary a lot in different depths. In tropical or semi-tropical areas, the temperature of seawater ranges from 24 °C to 29 °C, where the depth is between 0 and 50 m; but the temperature is 4–7 °C, where it is 500–1000 m deep [60,61]. The temperature difference remains about 20 °C by estimate. The differences form ocean's temperature gradient, and ocean thermal energy is generated. Ocean thermal energy is derived from solar energy, but it is more stable and less affected by seasons and day-to-night changes.

Ocean thermal energy can also be absorbed, and converted into electrical energy and other energy forms via ocean thermal energy conversion (OTEC) [62]. OTEC uses the difference to run a heat engine and produce useful work, like electricity. Many OTEC experimental apparatuses have been established in USA and Japan [63,64].

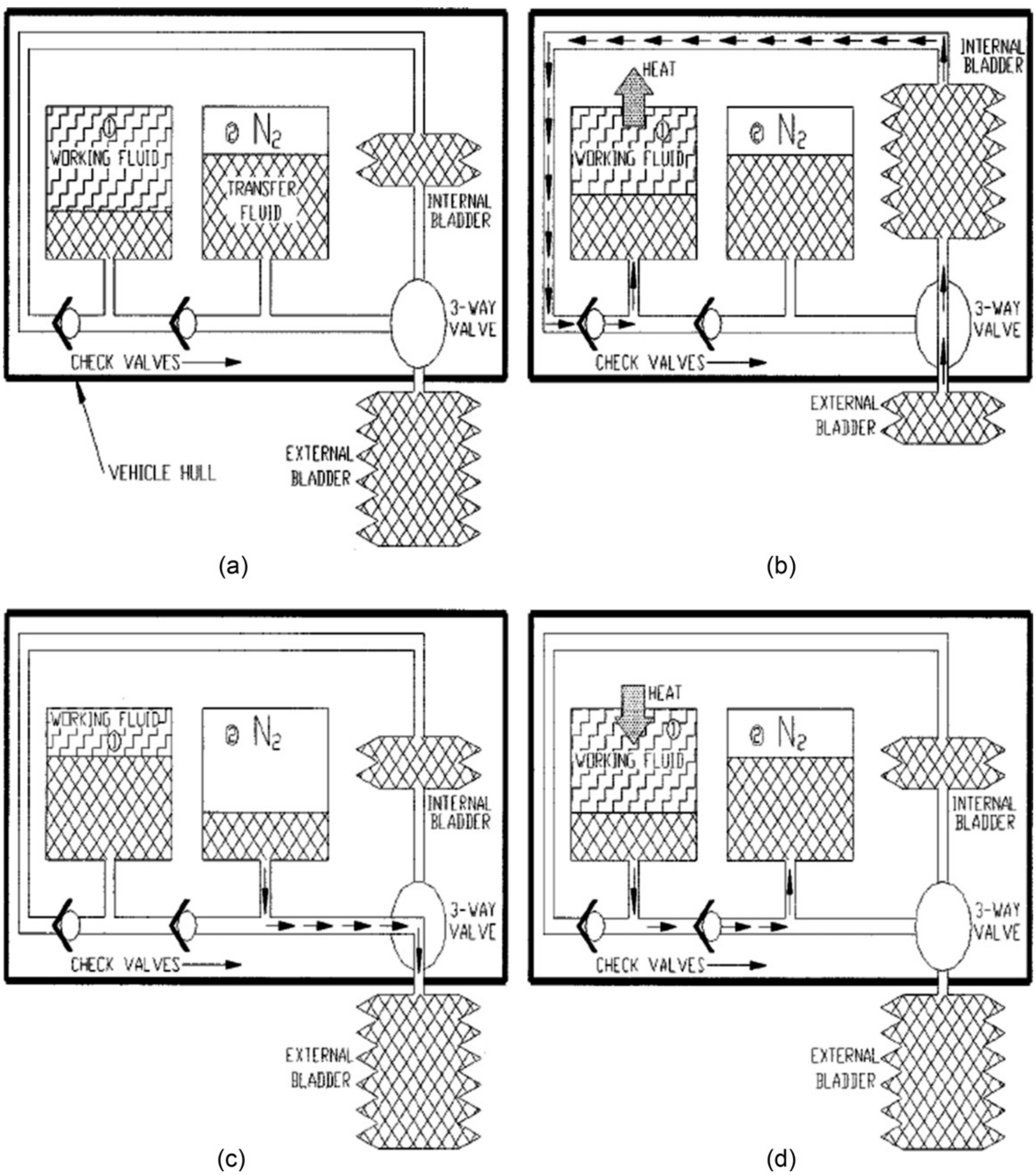

Fig. 9. The working process of thermal engine in Slocum Thermal.

a

Wind Speed (Kts)	Sea State	Significant Wave Height (Ft)	Significant Range of Periods (Sec)	Average Period (Sec)	Avg Wave Freq (Hz)	Average Length of Waves (FT)
3	0	<.5	<.5 - 1	0.5	2.000	1.5
4	0	<.5	.5 - 1	1	1.000	2
5	1	0.5	1 - 2.5	1.5	0.667	9.5
7	1	1	1 - 3.5	2	0.500	13
8	1	1	1 - 4	2	0.500	16
9	2	1.5	1.5 - 4	2.5	0.400	20
10	2	2	1.5 - 5	3	0.333	26
11	2.5	2.5	1.5 - 5.5	3	0.333	33
13	2.5	3	2 - 6	3.5	0.286	39.5
14	3	3.5	2 - 6.5	3.5	0.286	46
15	3	4	2 - 7	4	0.250	52.5
16	3.5	4.5	2.5 - 7	4	0.250	59
17	3.5	5	2.5 - 7.5	4.5	0.222	65.5
18	4	6	2.5 - 8.5	5	0.200	79
19	4	7	3 - 9	5	0.200	92
20	4	7.5	3 - 9.5	5.5	0.182	99
21	5	8	3 - 10	5.5	0.182	105
22	5	9	3.5 - 10.5	6	0.167	118
23	5	10	3.5 - 11	6	0.167	131.5
25	5	12	4 - 12	7	0.143	157.5
27	6	14	4 - 13	7.5	0.133	184
29	6	16	4.5 - 13.5	8	0.125	210
31	6	18	4.5 - 14.5	8.5	0.118	236.5

b

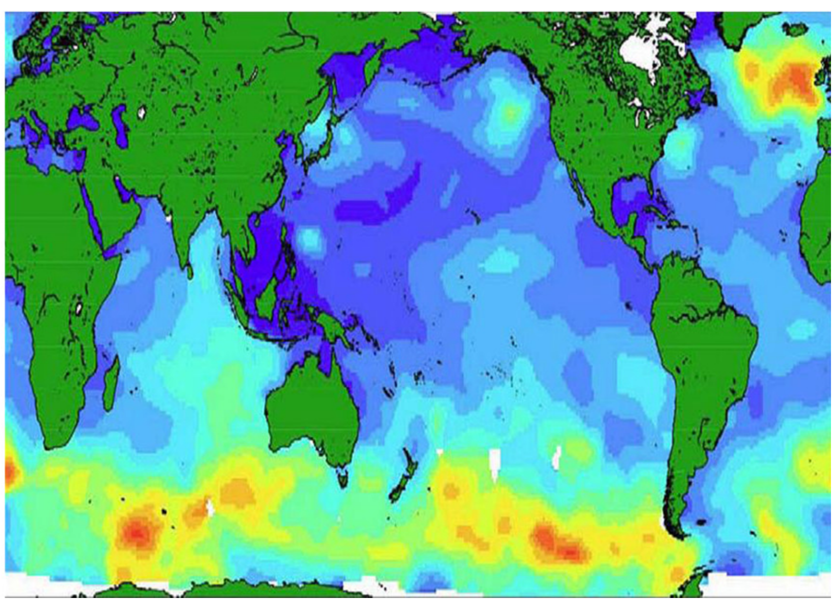

Fig. 10. (a) Sea state wave characteristics and (b) average global distribution.

Ocean thermal energy can also be used for power supply of underwater vehicles. Stommel has envisioned an underwater glider propelled by environmental energy [65]. It can harvest ocean thermal energy for its propulsion from the ocean's temperature gradient. The glider can move from days to seasons uninterruptedly. Several underwater vehicles powered by thermal energy were then designed and developed, such as Slocum Thermal Glider (shown in Fig. 8) and an underwater vehicle by Tianjin University [66].

Slocum Thermal was developed by Webb Research Cooperation (WRC). It uses temperature difference to change states between solid and gas, controlling the vehicle's buoyancy. In Slocum Thermal Glider, heat engine is the key part [54]. It consists of two chambers, pipes, valves and internal and external bladders. Chamber I is filled with working fluid and transfer fluid, and chamber II is an accumulator, filled with nitrogen and transfer fluid. The vehicle reaches cold water, heat flows out of the working fluid, which freezes, contracts, and draws in transfer fluid from the internal bladder. When it reaches the warm water, heat flows into the working fluid, which melts and expands. The engine works circularly, and the working process is exhibited in Fig. 9, and the buoyancy is controlled.

4.3. Wave energy

Wave energy, resulting from the transfer of energy from wind into water, represents a large potential source of energy for the world. It is related with sea state, including wave height and wave period. Fig. 10 shows the average global significant wave height, illustrating the potential for kinetic wave energy harvesting [67]. It is not restricted by time and places. Unlike solar energy and ocean thermal energy, it has a broader application.

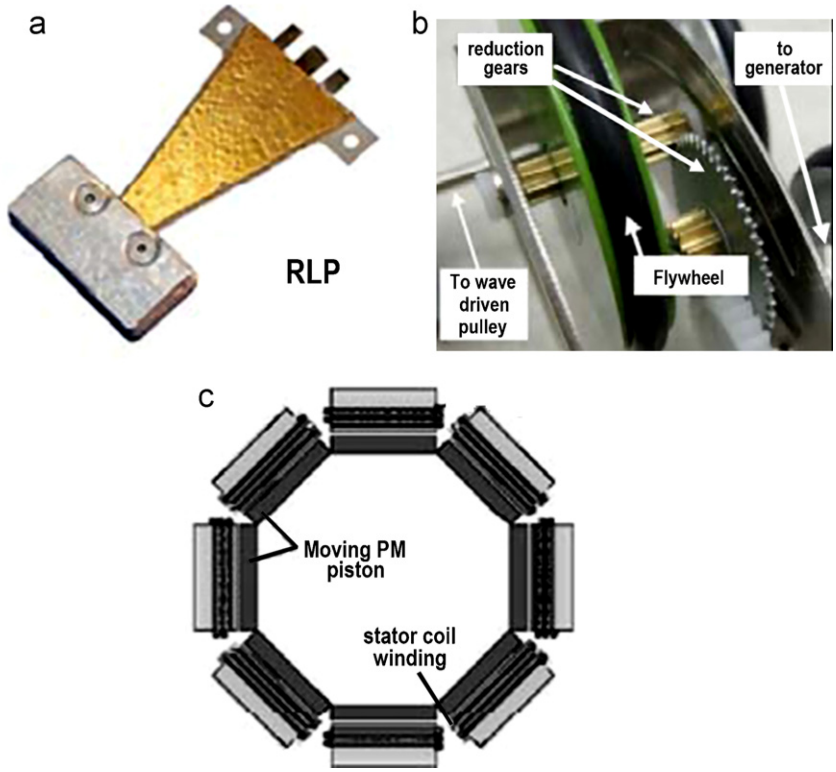

Fig. 11. (a) Piezo-ceramic for renewable energy conversion, (b) rotary generator for renewable energy conversion, and (c) linear generator for renewable energy conversion.

Wave energy can be absorbed and converted into electrical energy. The techniques have been researched for years, and some notable devices are also developed, such as oscillating body systems, OWC devices and overtopping devices [68]. Most of the devices are large-scale, especially for households and industrial applications. The electricity generation technologies for small-scale devices are also in development, there are shown in Fig. 11 [69]:

1) *Piezo-ceramic device*. It utilizes a newly developed ruggedized laminated piezo (RLP) device as the "micro-power" solution to convert relative wave motion to electrical energy. RLP is a mechanically simple design accommodated into a small volume.
2) *Rotary magnetic generator*. It is a traditional rotary geometry micro-generator with an innovative mechanism to continually spin the generator from the low frequency waves.
3) *Linear magnetic generator*. It is a novel magnet/coil device that can be deployed from the AN/SSQ-101 [69].

The AN/SSQ-101 Air Deployable Active Receiver is the most capable sonobuoy US Navy has ever deployed, and it is powered by micro ocean renewable energy (wave energy) for longer recovery windows. Chinese Academy of Sciences (CAS) also developed navigation light buoy BD102C powered buoy [70].

Wave energy can also be converted into electrical energy for underwater vehicles via wave energy conversion (WEC). Professor J.Z. Shang in National University of Defense Technology (NUDT) in China has proposed a mini wave energy conversion system (WECS), especially for ocean vehicles working for a long range and time [71]. The WECS is designed on the basis of Linear Wave Theory. A simplified wave can be decomposed as two simple plane waves perpendicular, one along the vehicle, and the other one vertical to the body. The device uses a 2-dof pendulum system as a wave absorber, capturing the motion as oscillations. It converts the oscillations into one-way rotation by a one-way device, and drives the generator. By using the pulse charging method [72], irregular electrical current is generated and accumulated in a secondary battery for storage. The model and principle are exhibited in Fig. 12.

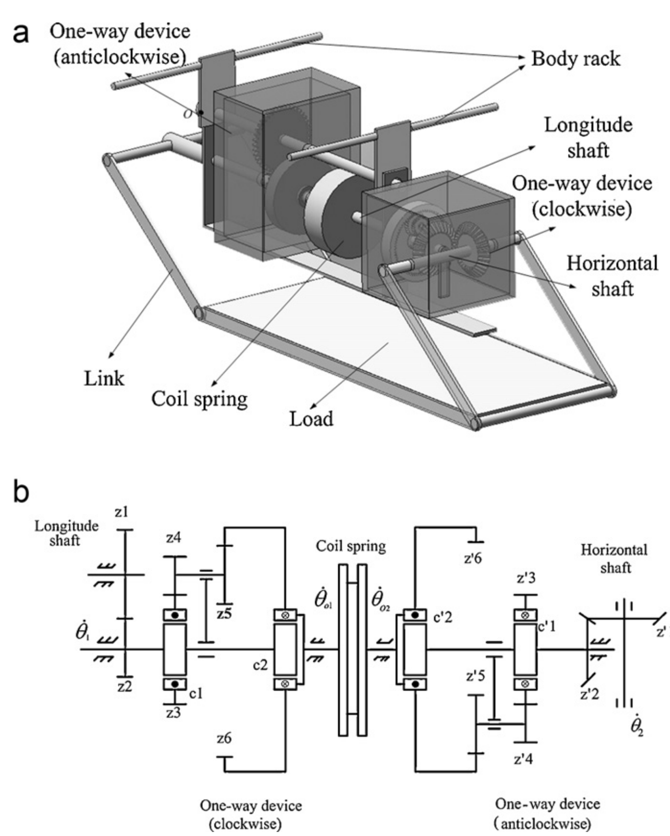

Fig. 12. (a and b) Model and working principle of a mini WECS.

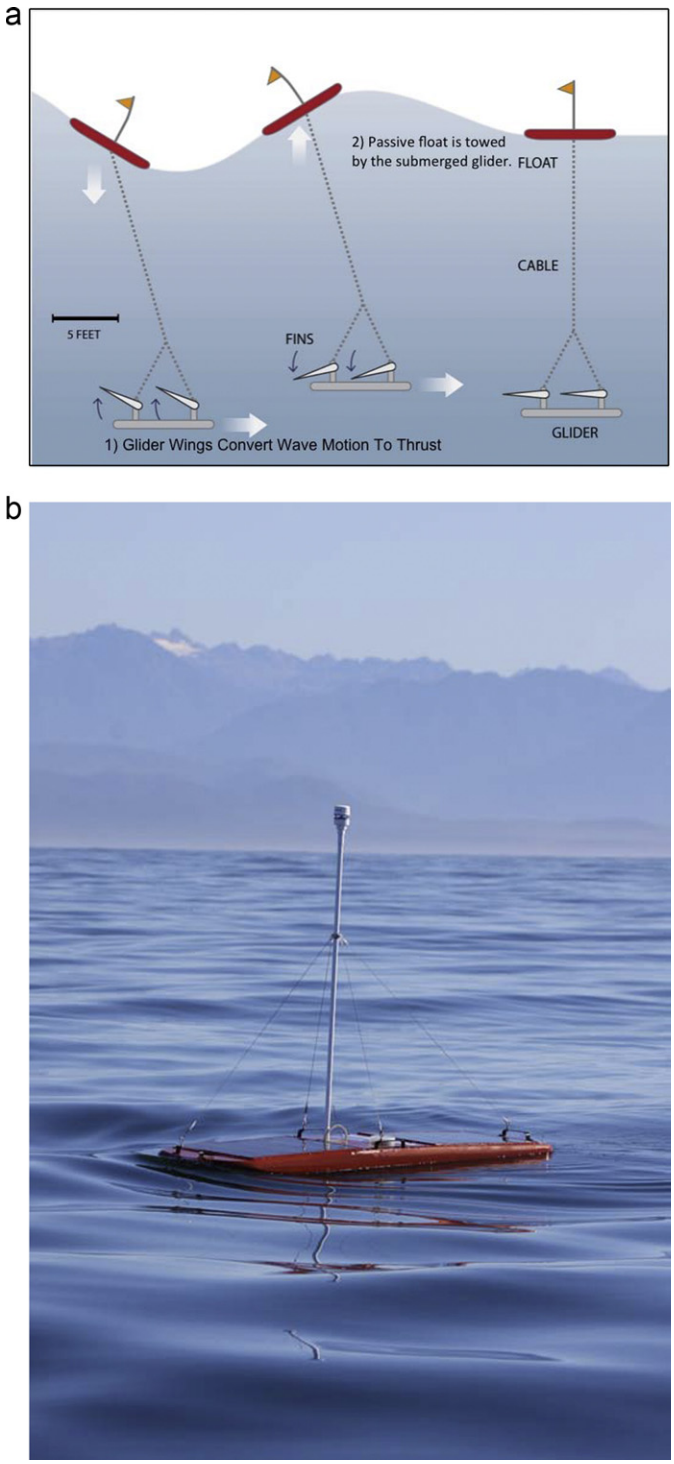

Fig. 13. (a and b) Wave glider and working mechanism.

Wave energy can also provide direct propulsion for unmanned underwater vehicles. Liquid Robotics Inc. has developed Wave Glider [73,74], as is shown in Fig. 13. It does harvest energy from ocean waves to provide essentially limitless propulsion and ensuing persistent presence at the air-sea interface. Wave Glider mainly has two bodies, a float on the sea surface and a submerged glider. These two bodies are connected via a tether. The glider can move forward by the conversion of ocean wave energy into forward thrust, like the forward motion of an airplane. It does not have a generator, and no electrical energy is generated.

However, the vehicle's navigation, control, communications and payload systems demand electrical power. Therefore, Wave Glider carries rechargeable lithium-ion batteries for the functions.

5. Docking stations for continuation

Batteries can provide electrical energy for these underwater vehicles. However, battery powered vehicles cannot work for long duration. The battery powered AUVs can only last tens of hours off shore, and the AUGs work for hundreds of days with little power consumption. Therefore, it is ideal to have a charger during the voyage course. A docking station is established to extend the vehicles' duration and guarantee the mission completion. It can provide many services, like data exchange, maintenance as well as power supply.

The AUV laboratory at MIT and WHOI firstly developed a docking station for Odyssey IIB AUVs [75]. Later on, kinds of docking stations or platforms are designed and constructed. WHOI has designed and built recharging stations for REMUS [76] and ABE [77]. Naval Ocean Systems Center (NOSC) in USA developed a docking system for AUV: free-swimmer [78]. Maridan ApS in Denmark also designed a system for euro-docker [79]. Kawasaki Shipbuilding Corporation in Japan also developed Marine Bird and its station [80]. George Hagerman proposed a novel docking platform, wave-powered AUV docking platform [81].

The Marine Bird docking station is built on the seafloor. It has V-shaped guide for porting and docking of the vehicle with catching arms. The batteries of the vehicle are then recharged via a couple of inductive connectors, which are connected by electromagnetic coupling. They transfer electrical energy from underwater base to the vehicle by electromagnetic induction of an alternating current. This recharging system also has an electromagnetic signal transfer unit to transfer the vehicle's status about docking and recharging. The overview of recharging system is shown in Fig. 14.

Wave powered AUV docking platform is a new concept of docking station, as is shown in Fig. 15. The docking platform is floating on the sea surface, equipped with 6 recharging stations. The recharging stations can provide power for 6 vehicles powered by batteries. The platform combines buoys with pre-tethered buoy moorings and fluid interconnections. It is based on submerging lower hull, which is an artificial seafloor [82]. The lower hull has dry compartments for energy storage system, including unitized regenerative fuel cells (URFC), compressed hydrogen and oxygen gas cylinders, and fresh water tanks. The saline water is pumped in under wave heave forces. It is then desalinated into fresh water as energy storage. The fresh water is ready for electricity generation by URFC technology utilization [83].

6. Challenges

Generally speaking, the techniques about power supply for unmanned underwater vehicles are appropriate and suitable for certain applications. They own unique advantages and drawbacks.

Tether power system. It is probably the safest and most matured way for ROVs. It can provide unlimited operation time, no considering the power limitation. It reduces on-board packaging, power and mass requirements. Besides, tethering guarantees much better communications than wireless way does. However, there are also some drawbacks: (1) the working range is limited by tether length; (2) tether may be twisted or broken; and (3) it needs reel systems for tether extension and retrieve. External forces on the systems may result in indeterminate motions. It will complicate path planning and motions, even prevents the system extrication.

Batteries. Battery is desirable to provide power for vehicles, as is represented in Section 3. However, the battery technologies still

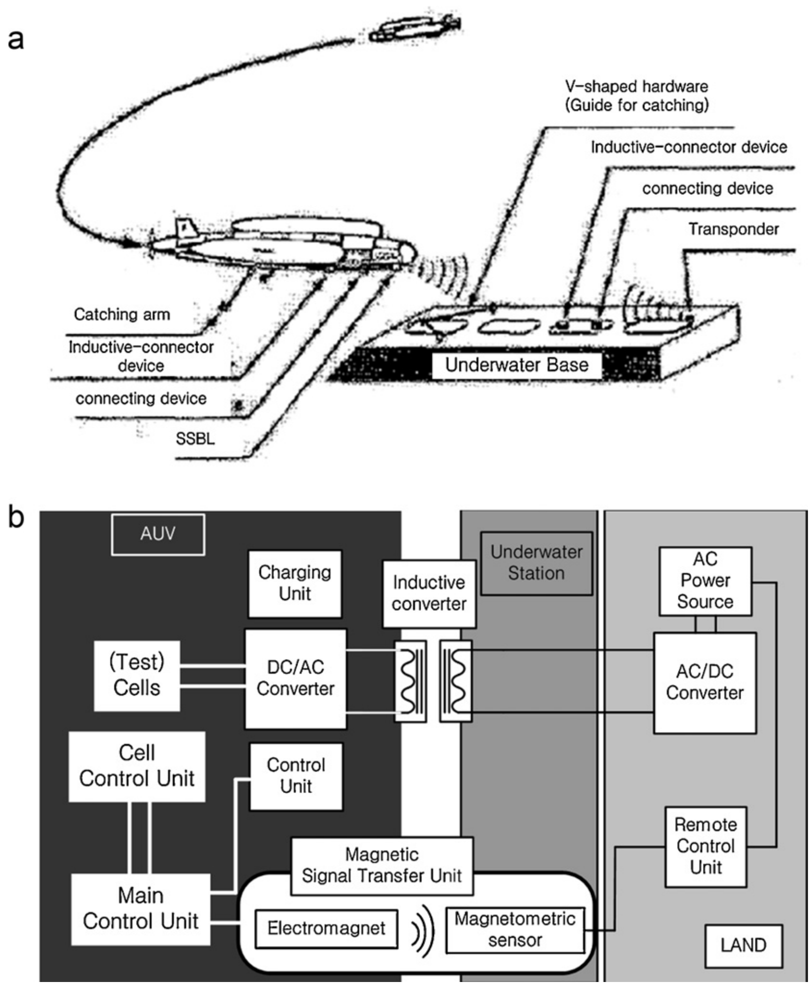

Fig. 14. Docking station for marine bird: (a) docking process and (b) the charging way.

need improving. There are still many batteries with insufficient energy density, limited numbers of cycles before failure and a poor shelf life. They cannot provide enough power for vehicles' duration. Some batteries are desirable with much higher energy density, such as lithium series cells and semi fuel cells. But they are not cost-effective in scientific research, because they cost too much. Spray Glider powered by lithium primary cells needs about $2850 in refueling, quintuples the cost of Slocum powered by alkaline cells [84]. Besides, batteries with noxious chemical substances may cause environment pollutions, like lead-acid cells [20].

Environmental energy is quite a novel way to power underwater vehicles. It is huge, clean and renewable, and potential to help the vehicle complete a long duration mission, even an unmanned station keeping mission. Solar energy, ocean thermal energy and wave energy and the conversions are represented in Section 4. They have both advantages and limitations, respectively.

Solar energy conversion. Solar energy is quite feasible for underwater vehicles' power supply. However, there are still some limitations. The conversion of solar energy into electrical energy is restricted by time, and it can only be completed in daylight. The amount of solar energy available on the ocean surface varies significantly with areas, seasons and weather, which is caused by solar radiation distribution. Besides, the conversion efficiencies available by solar panels are among 10–12%, not satisfying. Panels are always installed together to obtain more energy. Therefore, it demands that the vehicle a large and enough room for panels installation.

Ocean Thermal Energy Conversion. Ocean thermal energy was chosen since it is reliably and predictably available at all hours. It can be harvested while underway. However, the limitation is that the temperature gradient is not available globally. It can only be satisfied in tropic and semi-tropic areas. That is because the temperature difference it needs must be greater than 10 °C between surface and depth [54]. Therefore, the vehicle powered by thermal energy can only be used between 35° south latitude and 35° north latitude.

Wave energy conversion. Wave energy is much better than solar energy and ocean thermal energy. It is not restricted by time or places. It can provide energy source for underwater vehicles at any time and any place in theory. However, harvesting wave energy is quite a difficult process, because it is dispersive and random. Besides, the conversion efficiency is quite low due to energy loss, which is caused during energy delivery stages. It is necessary to simplify the conversion process and minimize the energy loss to improve the efficiency.

7. Futures

As is represented in Section 5, environmental energy conversion is the most promising choice of power supply for unmanned underwater vehicles. It is giant, clean and regenerative, and has a brighter future and more applications.

(1) Environmental energy for ROVs. As is known to us, ROVs are powered via tethers from LASH ships. The electrical power is carried from the shores or generated in a LASH ship, which is

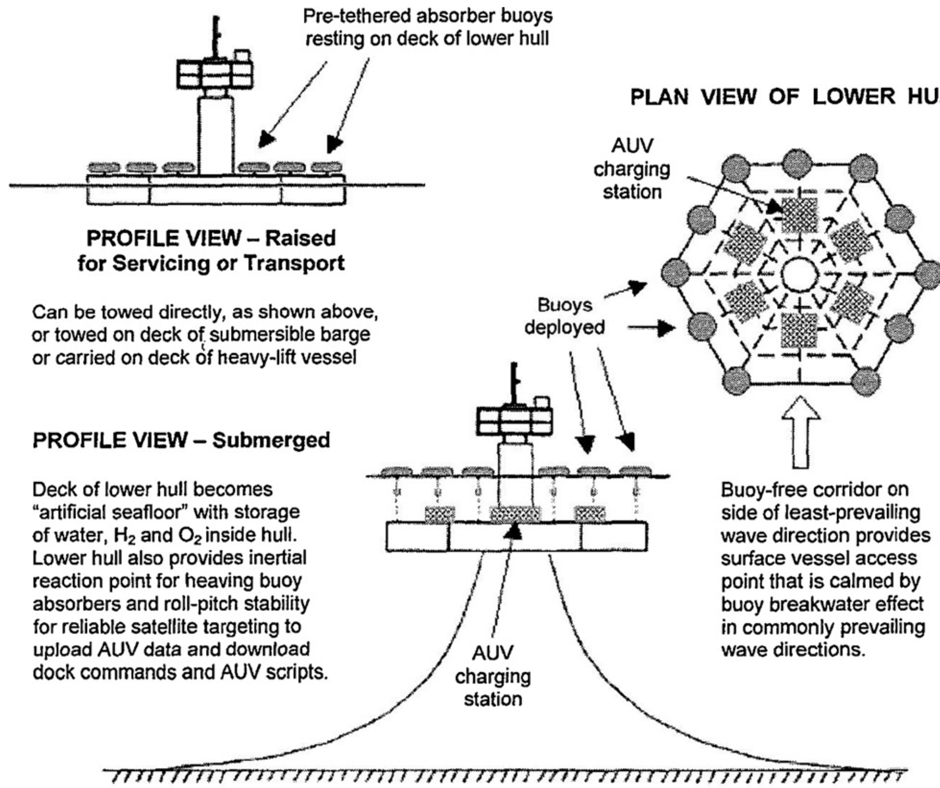

Fig. 15. Wave-powered docking platform.

also limited in capacity. Instead of that, the electrical power can be obtained by the environmental energy conversion, such as wave energy, solar energy and thermal energy. For example, a floated type OWC device can be used in a LASH ship.

(2) Docking station by environmental energy. Docking station is designed and established to provide continuation and data exchange for UUVs. The electrical power is imported from shores by cables, costly and complicated. As is proposed by George Hagerman, wave energy can be captured and converted into electrical power or some other energy sources for the vehicles. Besides, solar panels and heat engines are also applied to generate electrical power from solar energy and thermal energy.

(3) Environmental energy conversion devices installed on underwater vehicles. It is a good idea to develop an energy conversion device installed on the vehicle. When floating on the surface, the device can absorb environmental energy and convert it into electrical power. Solar panels can be installed on the surface of the vehicle. A mini WECS can be installed inside the vehicle. Combining battery techniques, electrical power generated can be commutated and work for vehicles. By applying ocean thermal energy, a heat engine can also change the vehicle buoyancy to drive an underwater vehicle.

8. Conclusions

Power systems of UUVs have been researched and developed for many years. The three ways of power supply in the paper are most popular at present. They are possessed with some advantages and limitations, and applied in different situations.

After a careful research about these systems, environmental energy is selected as the right one to apply in underwater vehicles. Wave energy is available almost all hours and almost everywhere on the sea surface. It can be captured and converted into electrical power and other power, which is used to power vehicles or charging batteries in docking stations. The conversion efficiency is quite low, because energy loses during delivery stage. Therefore, simplifying the conversion process and minimizing the energy loss is the key point in environmental energy conversion research. Additionally, the electric current is needed to be commutated for use.

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